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Couplings and beyond the Standard Model Higgs production at LHC

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Abstract

The large centre-of-mass energy and luminosity provided by the Large Hadron Collider will provide a unique opportunity to search for evidence of physics beyond the Standard Model. This talk will focus on the potential to discover and measure the properties of the Higgs bosons expected in models, such as the Minimal Supersymmetric Standard Model.

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1 Introduction

The origin of the mass of fundamental particles, whose electroweak and strong interactions are explained by the Standard Model (SM), is believed to be the electroweak symmetry breaking mechanism, which predicts the existence of a new particle, namely the Higgs boson [1]. Although the SM has been successfully tested experimentally, no direct evidence for the existence of the Higgs has been found. Despite the success of the SM, it still has some significant shortcomings, indicating that further extensions to the SM are required. For example, the mass of the Higgs is expected to be of the order of the electroweak scale in the SM, a fact that is borne out by precision electroweak data [2]. However, the fermionic 1-loop corrections to the tree-level Higgs mass are quadratically divergent, shifting the bare Higgs mass up to the order of the Planck mass. A mechanism is therefore required to cancel out these corrections. A number have been proposed [3], the most popular of which is Supersymmetry [4], which introduces a new set of fundamental particles, completely cancelling out the divergent loop corrections. Other possible solutions include the five-dimensional Randall-Sundrum model [5], in which all mass terms near the Planck mass are suppressed by an exponential factor, bringing them down to the TeV scale, and the Littlest Higgs model [6], in which the SM Higgs remains light and a small set of new heavy particles is introduced, cancelling out the most significant loop corrections to the SM Higgs mass. However, only supersymmetry offers a complete solution to this hierarchy problem, while the other models shift the problem to higher scales.

The Large Hadron Collider (LHC) at CERN in Geneva, Switzerland, is currently under construction, with the primary goal of finding evidence for the existence of the Higgs boson, as well as for signs of new physics at the TeV scale. The LHC will collide two 7 TeV proton beams every 25 ns, making it the highest energy accelerator ever. Two general-purpose detectors, ATLAS and CMS, are being constructed to detect and analyse the results of these collisions. Both the machine and the experiments are in an advanced state, with first data-taking expected in 2008.

2 The Higgs Sector of the Minimal Supersymmetric Standard Model

In the Minimal Supersymmetric Standard Model (MSSM) two complex Higgs doublets are needed to give masses to the fermions. This leads to five physical Higgs bosons: Three neutral states – the CP-even h^0 and H^0 and the CP-odd A^0 – and two charged states, H^\pm . The MSSM Higgs sector can therefore be described by four masses and two mixing angles: β , where $\tan \beta$ corresponds to the ratio of the vacuum expectation values of the two doublets and α , which describes the mixing in the neutral, CP-even sector.

At leading order (LO), only two of these parameters are independent and by convention these are taken to be $\tan \beta$ and the mass of the A , M_A . A number of mass hierarchies also apply: $M_h < M_Z$, $M_A < M_H$ and $M_{W^\pm} < M_{H^\pm}$. However, radiative corrections, stemming mainly from the t/\tilde{t} sector, increase the upper bound on the light neutral Higgs to $M_h \simeq 135 \text{ GeV}/c^2$ [7]. The light neutral Higgs reaches this bound at large values of M_A where it becomes SM-like in its behaviour. At next-to-leading order (NLO), additional parameters are required. Given that the dominant NLO corrections to the mass come from the t/\tilde{t} sector, the most important of these parameters are: M_{top} , the top mass, X_t , the stop mixing parameter, M_2 , the SU(2) gaugino mass at the electroweak scale, μ , the Higgs mass parameter, M_{gluino} , the gluino mass and M_{SUSY} , the soft SUSY-breaking parameter in the sfermion sector at the electroweak scale.

Rather than attempting to vary all these parameters independently, a number of so-called “benchmark” scenarios have been defined, where $\tan \beta$ and M_A are scanned, while the other parameters remain fixed. The results presented here are based on the so-called M_h^{max} scenario [8], which was also used at LEP [9] as it gives rise to the most conservative exclusion limits on M_h . The values for the key fixed parameters for this scenario are: $M_{top} = 175 \text{ GeV}$, $M_{SUSY} = 1 \text{ TeV}$, $\mu = 200 \text{ GeV}$, $M_2 = 200 \text{ GeV}$, $M_{gluino} = 0.8 M_{SUSY}$ and $X_t = 2M_{SUSY}$, assuming the on-shell (OS) renormalisation scheme. A number of other scenarios have also been considered [10].

3 Neutral Higgs Production in the MSSM

At small and moderate values of $\tan \beta$, the gluon fusion process, $gg \rightarrow h/H/A$, is the dominant production mechanism for the neutral Higgs bosons. The process is mediated by top or bottom loops, but can also be mediated by stop and sbottom loops for the scalar Higgs bosons (h and H) if the squark masses are low enough [11]. The vector boson fusion process, $qq \rightarrow qq + WW/ZZ \rightarrow qq + h/H$, plays an important role in the production of the scalar Higgs boson, $h(H)$, when it is close to its upper(lower) mass bound. This process does not take place for the pseudoscalar Higgs, due to CP-invariance.

At large values of $\tan\beta$, the production of a Higgs in association with a $b\bar{b}$ pair is the dominant Higgs production mechanism. The corresponding process with a $t\bar{t}$ pair is only important for the production of the light scalar Higgs, but over the full $\tan\beta$ range.

Data from the LEP experiments have placed constraints on the light neutral Higgs to lie close to its upper mass bound and hence to be SM-like. This means that the results of SM Higgs searches can be used to determine the discovery potential for the h in the MSSM. The most promising decay channels in these direct searches are those to leptons or gauge bosons, as these are much easier to identify experimentally than the dominant decay to $b\bar{b}$. The decays to $\tau^+\tau^-$, $\gamma\gamma$ and W^+W^- are of particular interest, with the decay to τ^\pm leptons giving particularly good reach. In the M_h^{\max} scenario, the $\tan\beta - M_A$ plane is well-covered in the region $0.5 \leq \tan\beta \leq 50$ and $M_A \leq 800 \text{ GeV}/c^2$ for an integrated luminosity of 30 fb^{-1} .

While much of the low $\tan\beta$ region has been excluded by LEP, the large $\tan\beta$ region is much less constrained. One of the most interesting processes to study in this region is the process $gg/qq \rightarrow b\bar{b}\Phi$, $\Phi \rightarrow \mu^+\mu^-$, when $\Phi = H/A$. This is because in this region the decay to $\mu^+\mu^-$ gives the best measurement of both the mass and the width of the heavy neutral Higgs. For example, at a dimuon mass of $200 \text{ GeV}/c^2$, the resolution is expected to be only 1.8 %. At large $\tan\beta$, the width is comparable to or larger than the experimental mass resolution. At large $\tan\beta$ the width depends on $\tan\beta$, which means that measurements of this process can be used to place constraints on the value of $\tan\beta$. Figure 1 shows the uncertainty on $\tan\beta$ that can be obtained assuming the M_h^{\max} scenario for an integrated luminosity of 30 fb^{-1} and including a 15% theoretical uncertainty. The good mass resolution is also important in the “intensive coupling” regime [12], in which all of the Higgs bosons are almost degenerate in mass. The decay to $\mu^+\mu^-$ offers the only possibility of being able to distinguish between the different Higgs mass peaks, providing the mass differences are larger than $3 - 4 \text{ GeV}/c^2$.

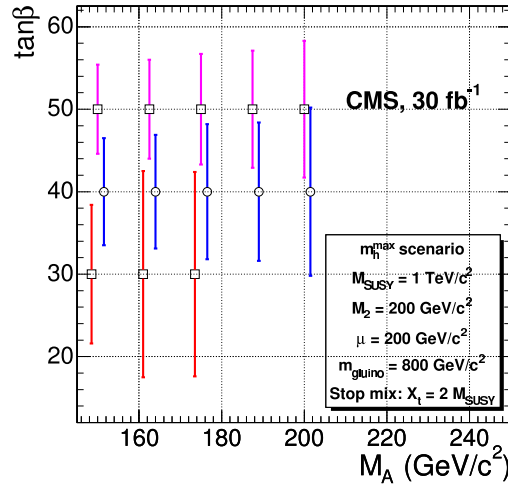


Figure 1: Uncertainty on the $\tan\beta$ measurement obtained from the Higgs boson width measurement with an integrated luminosity of 30 fb^{-1} for three different values of $\tan\beta$ and five different values of M_A in the M_h^{\max} scenario.

The low $\tan\beta$ region has not been completely excluded by LEP. In this region, the decay $A \rightarrow Z^0 h$ has a large branching ratio in the mass range $M_Z + M_h \leq M_A \leq 2M_t$ and allows the simultaneous observation of two of the three neutral Higgs bosons. Assuming $\mu = M_2 = 600 \text{ GeV}/c^2$ in the M_h^{\max} scenario (this choice avoids regions of the low $\tan\beta$ phase space in which the decay to charginos and neutralinos dominates), the discovery potential reaches $\tan\beta = 2.5$, covering the low $\tan\beta$ region not excluded by LEP.

4 Charged Higgs Production in the MSSM

When charged Higgs production is studied, two different regions are used: $M_{H^\pm} < M_t$ and $M_{H^\pm} > M_t$. In the former, the Higgs is predominantly produced in the process $gg \rightarrow t\bar{b}H^\pm$, which includes on-shell $t\bar{t}$ production with a subsequent decay to $t \rightarrow bH^\pm$. In the latter region, the dominant production mechanism is $gb \rightarrow tH^\pm$. The region around $M_{H^\pm} \simeq M_t$ has not previously been considered for analysis because the process $gg \rightarrow t\bar{b}H^\pm$ actually forms part of the higher order corrections to the LO process $gb \rightarrow tH^\pm$. As such, the transition region around M_t requires careful theoretical handling in order to avoid double counting [13, 14]. This has been implemented

in the Monte Carlo program MATCHIG [15], which has been interfaced to PYTHIA [16] and used by the ATLAS Collaboration to study the discovery potential in the region $165 < M_{H^\pm} < 600 \text{ GeV}/c^2$, that is, including the transition region. The decay to the $\tau^\pm \nu$ final state was used as it is experimentally much cleaner than the $H^\pm \rightarrow tb$ case. Figure 2 shows the 5σ discovery potential for this process assuming two different integrated luminosities, from which it can be seen that charged Higgs masses below $160 \text{ GeV}/c^2$ will be observable, regardless of $\tan \beta$. Figure 2 does not include systematic uncertainties, but detailed studies performed for $\tan \beta = 35$ show that these reduce the significance by 30-60% depending on the charged Higgs mass, if the most pessimistic assumptions are applied.

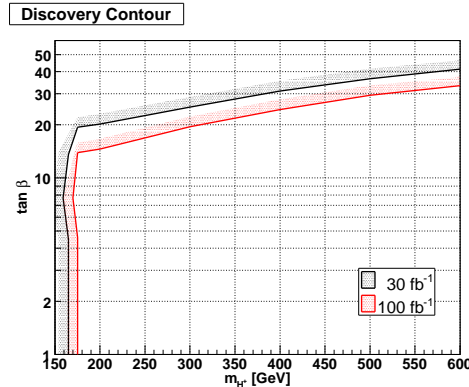


Figure 2: Charged Higgs boson discovery contour M_{H^\pm} versus $\tan \beta$ in the MSSM. The regions above the curves are the regions in which a 5σ discovery is feasible. The results, shown for two different integrated luminosities, do not include systematic uncertainties. The shape of the curves is determined by the cross section for charged Higgs production, which increases rapidly with decreasing Higgs mass.

5 Higgs Couplings

A study has been performed [17] which investigates the possibilities for measuring the couplings of the Higgs, assuming a general multi-Higgs doublet model. A wide range of processes, studied by both ATLAS and CMS, are used, including a number of analyses based on the vector boson fusion production process. These couplings are then proposed as a method of distinguishing between the SM Higgs and the light neutral Higgs in the MSSM. This study is based on the M_h^{max} scenario and assumes, for simplicity, that the pseudoscalar and charged Higgs bosons are significantly heavier than the light scalar Higgs ($M_A > 150 \text{ GeV}/c^2$). It is also assumed that the mass of the Higgs has been well-measured. A χ^2 analysis of the measured couplings was performed to determine in which regions of phase space a discrepancy with respect to the SM could be observed. Figure 3 shows the region in which a greater than 3σ discrepancy would be observed for three different luminosity scenarios. The “ $2 * 30 \text{ fb}^{-1}$ ” and “ $2 * 300 \text{ fb}^{-1}$ ” scenarios correspond to each experiment having a dataset corresponding to either 30 fb^{-1} or 300 fb^{-1} . The “ $2 * 300 + 2 * 100 \text{ fb}^{-1}$ ” scenario assumes a 300 fb^{-1} dataset for each experiment, but assumes that only 100 fb^{-1} per experiment is useable for vector boson fusion analyses. The reason for considering this scenario is that the analysis performance is expected to be significantly degraded for vector boson fusion processes in the high luminosity scenario. This is important because analyses of vector boson fusion processes give the best measurements of the couplings and hence are the most sensitive to any discrepancies in the χ^2 analysis.

6 Higgs Production in Non-Supersymmetric Models

The CMS Collaboration have performed Higgs search studies based on two non-supersymmetric extensions to the SM. One is based on the five-dimensional Randall-Sundrum model, which includes the SM Higgs, h , and the radion, Φ , a scalar field that describes fluctuations in the metric in the fifth dimension. The study was performed using the process $gg \rightarrow \Phi \rightarrow hh$, in which it was assumed that one Higgs decayed to $b\bar{b}$, while the other decayed either to $\gamma\gamma$ or $\tau^+\tau^-$. Fixing the Higgs mass to $120 \text{ GeV}/c^2$ and the radion mass to $300 \text{ GeV}/c^2$, the $\Lambda_\Phi - \xi$ plane can be scanned, where the former is the vacuum expectation value of the radion field and the latter is the radion-Higgs mixing parameter. Based on an integrated luminosity of 30 fb^{-1} it was found that the $b\bar{b}\gamma\gamma$ final state gives the best reach and that this final state would allow a 5σ discovery in a region of phase space complementary to that accessible to an inclusive $h \rightarrow \gamma\gamma$ analysis for the same integrated luminosity.

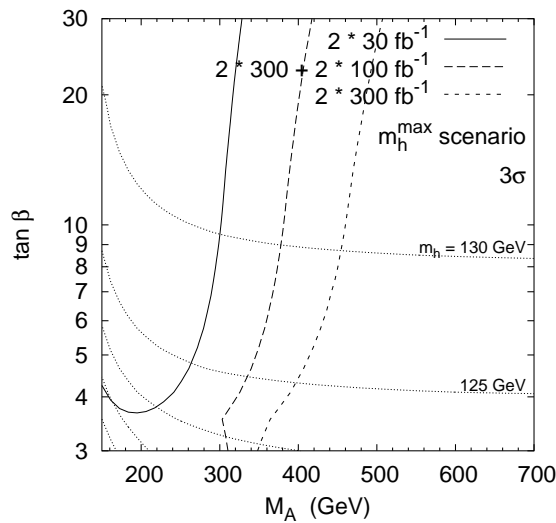


Figure 3: Results of the fit within the M_h^{\max} scenario in the M_A - $\tan\beta$ plane for three luminosity scenarios. The plot shows the region (to the left of the curves) which would yield a $\geq 3\sigma$ discrepancy from the SM. The almost-horizontal dotted lines are contours of M_h in steps of 5 GeV.

The CMS Collaboration have also performed a study based on the Littlest Higgs model. This model explicitly predicts the existence of a doubly-charged Higgs, $\Delta^{\pm\pm}$, whose dominant production mechanism is via the Drell-Yan process, $pp \rightarrow \Delta^{++}\Delta^{--}$. This process was used, with each $\Delta^{\pm\pm}$ decaying to like-sign muon pairs, to study the discovery potential as a function of the $\Delta^{\pm\pm}$ mass. It was found that for an integrated luminosity of 10 fb^{-1} , it will be possible to discover the doubly-charged Higgs up to a mass of $650^{+0.4}_{-0.3}(\text{bkgd})^{+3.0}_{-0.4}(\text{signal}) \pm 0.2(\text{lumi}) \text{ GeV}/c^2$. Turning this around, this can be expressed as an exclusion limit of $760^{+0.5}_{-2.0}(\text{bkgd}) \pm 10(\text{signal}) \pm 4(\text{lumi}) \text{ GeV}/c^2$. This value represents a significant improvement on the existing limit from the CDF Collaboration of $136 \text{ GeV}/c^2$ [18].

7 Summary

A wide range of studies have been performed by the ATLAS and CMS Collaborations to determine the discovery reach for beyond the Standard Model Higgs boson production. In particular, the Minimal Supersymmetric Standard Model has been extensively explored, primarily in the M_h^{\max} benchmark scenario, but also in a number of other scenarios. The results from the two Collaborations suggest that good coverage of the MSSM phase space will be achieved, with the final states including τ^\pm leptons giving particularly good discovery potential. It should also be possible to constrain $\tan\beta$ using the process $b\bar{b}H/A, H/A \rightarrow \mu^+\mu^-$.

A study of Higgs couplings has been performed in which the SM Higgs couplings can be used to determine whether a discovered Higgs boson is from the SM or from the MSSM. It should be possible to observe a $> 3\sigma$ discrepancy with respect to the Standard Model for masses up to $M_A \simeq 450 \text{ GeV}/c^2$.

Some studies have also been performed based on non-supersymmetric extensions to the Standard Model. In particular, the discovery potential for Higgs production in the five-dimensional Randall-Sundrum model has been investigated, indicating that Higgs decays to two photons give the best reach. Studies of doubly-charged Higgs production in the Littlest Higgs model have shown that the existing exclusion limit can be increased by a factor of almost six for a relatively modest integrated luminosity.

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